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CONSTRUCTION OF A HIGH PERFORMANCE RESISTOJET FOR SATELLITE PRO--ETC(U)
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PROPELLANTS, EXPLOSIVES AND ROCKET MOTOR ESTABLISHMENT
WESTCOTT

Technical Report No. 99

CONSTRUCTION OF A HIGH PERFORMANCE RESISTOJET FOR SATELLITE PROPULSION

by

P.J. Sherwood

SUMMARY

The fabrication and assembly of a 3 kW resistojet thruster employing hydrogen as a propellant are described with particular reference to the materials problems involved. Rhenium has been selected as the most suitable material for the concentric tubular heat exchanger which must operate at temperatures up to 2500 K in flowing hydrogen for a minimum period of 2000 hours, with temperature cycling.

Because of the complex geometry and close tolerances required, thin walled rhenium tubes were made by a chemical vapour deposition technique. Rhenium parts were joined by electron beam welding.

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3

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CONTENTS

1 INTRODUCTION

PERME Westcott retained an interest in satellite propulsion until 1973. A paper[1] briefly describing the operating principles and materials requirements of a high performance electrothermal rocket, the hydrogen resistojet, was published in 1969 and another[2] concerned with resistojets combined with ion motors in 1970. The performance testing of a 3 kW resistojet, which employed a concentric tubular heat exchanger and nozzle fabricated from pure rhenium, was also reported[3,4] but an account of the selection of materials for such purposes and the specialised fabrication techniques which had to be developed for rhenium was not formally recorded. This report rectifies that omission.

2 DESIGN CRITERIA

The principal performance objective was to achieve, at an electrical power level of 3 kW, the highest specific impulse consistent with a thrust of 0.65 N, a service life of at least 2000 hours, and at least 400 power interruption cycles. The initial design parameters shown in Table 1 were submitted to a company in the USA, Advanced Rocket Technology, Irvine, California, which carried out a design study to produce the resistojet, designated J3, shown in Fig. 1. A stress analysis (Table 3) showed that at the hydrogen supply pressure of 0.891 MN/m^2, creep in the high temperature rhenium parts serving as pressure vessels was likely to cause failure within 2000 hours, so the design pressure was reduced to a safe level of 0.345 MN/m^2 resulting in the revised parameters shown in Table 1. In previous 8000 hour service life tests[5] on 0.3 kW resistojets, creep of rhenium parts had been found to be the life-determining factor. A more detailed description of the design analysis for this resistojet is given in Ref. 6.

2.1 Resistojet design

A list of the components, showing their materials of construction and masses, is given in Table 2. Rhenium components made by a chemical vapour deposition process are marked CVD. Other rhenium parts in which sintered and rolled sheet was the starting material are labelled 'sintered'.

The design incorporates a number of features developed on a 0.3 kW resistojet[7]. To reduce heat loss in the radial direction a vacuum jacket filled with radiation shields is placed around the concentric tube heat exchanger. This produces a steep radial temperature gradient which causes differential thermal expansion of the tubes along their axis. If it were not compensated for, this differential expansion would cause buckling of the tubes, so a stainless steel

bellows is incorporated to take up this expansion. To remove any axial loads on the rhenium tubes at their operating temperature, the bellows is located so that it is evacuated to space internally and has the hydrogen supply pressure, P , acting on the exterior. The bellows spring constant, k , and effective area A are then chosen so that the forces due to the net thermal expansion, δ , of the tubes (approximately 0.5 mm) are balanced by the pressure differential forces, PA . Thus

$$PA \simeq k\,\delta \quad . \qquad (1)$$

A metal/ceramic seal of a type frequently used in the electronics industry is incorporated around the thermal expansion compensator to provide a gas-tight electrically insulated seal. It consists of nickel-iron alloy tubing brazed to an alumina ring. A five pass heat exchanger is used in place of the three pass geometry of the 0.3 kW resistojet, so that the outside of the nozzle is not cooled by the incoming hydrogen gas.

The propellant supply tube (4) also serves as one electrical terminal. The thermal dam (3) prevents thermal loss to either the propellant line or the power cable attached to it. The other electrical terminal is attached to the rear of the inner case stem (25) by another thermal dam, not shown.

The high temperature heat exchanger, consisting of heating elements 8, 17, 9 and 10, is thermally insulated by an evacuated space ($< 10^{-4}$ torr) filled with radiation shields (21) made from spirally wrapped rhenium foil. The shields are electrically insulated from the inner case (19) by a thin boron nitride sleeve.

The inner assembly is centred in the steel mount (2) by a boron nitride insulator bearing (1) through which the stem passes. The first external thermal insulation consists of coaxial layers of Dyna-quartz (a silica based rigid insulant of low thermal conductivity) while the second consists of Min-K 2000 (a fibrous insulation) contained in the stainless steel can.

The recommended assembly procedure is given in the Appendix.

2.2 Selection of materials

For the heat exchanger, only tungsten and rhenium have the necessary electrical conductivity combined with high temperature creep strength, low sublimation rate and chemical compatibility with hydrogen. Tungsten has the disadvantage, however, of a high ductile-brittle transition temperature, particularly after heating above 2000°C, combined with a tendency to crack

during welding. Therefore rhenium was used because of its low temperature ductility and weldability, which make it ideal for withstanding launch vibrations and thermal cycling.

Boron nitride was selected for electrical insulator parts because of its high temperature stability and compatibility with rhenium, ease of machining and resistance to thermal shock. Grade HP, manufactured by the Carborundum Co., was used because of its thermal shock and moisture resistance.

A molybdenum - ½ per cent titanium alloy was selected for part 25 because of its low electrical resistivity, high strength and relatively good machineability. An austenitic 18/8 stainless steel to Spec. S.130 (niobium stabilized) was used for other parts because of its strength, weldability and resistance to corrosion.

3 FABRICATION OF RHENIUM COMPONENTS

Rhenium, although ductile in the fully recrystallized condition, has the highest measured work hardening rate of any metal. This, combined with its susceptibility to rapid oxidation above 600 to 700 K, makes the fabrication of rhenium components by conventional metal working processes difficult, necessitating frequent recrystallizing annealing steps in hydrogen or vacuum. Although wrought products from pressed and sintered rhenium are readily available in the form of rod, wire and sheet, more complex shapes such as thin wall (0.1-0.2 mm) seamless tubes are not available. The inner heat exchanger parts of the resistojet, and the nozzle were therefore made by a chemical vapour deposition (CVD) process.

3.1 Parts made by chemical vapour deposition

In this process a mixture of a rhenium halide gas and hydrogen is passed over a heated mandrel on which the gases react to deposit a layer of pure rhenium at a controlled rate (0.01-0.1 mm/hour). The mandrel can be subsequently leached out to provide a free-standing rhenium part. The advantages of the CVD process are i) parts of complex geometrical shape (e.g. the nozzle) can be made in one piece; ii) internal dimensions can be reproduced to close tolerances; iii) for small quantities, tooling costs are reduced by the use of expendable mandrels.

Initially, two sets of parts 8, 9, 10, 16 and 17 were vapour deposited by the San Fernando Laboratories, California, USA. Part 8 was deposited in two pieces because the increase in wall thickness to 1 mm on the flared end necessitated deposition in two runs. One set of parts after diamond grinding

and removal of the mandrels is shown in Fig. 2. The parts were deposited on a suitable mandrel material such as titanium at a temperature of approximately 975 K using the following gas reaction:

$$5\,H_2 + 2\,ReCl_5 \rightarrow 2\,Re + 10\,HCl \quad .$$

After deposition, the rhenium coatings were ground to the correct wall thicknesses using diamond abrasive wheels, and the mandrels were removed by dissolving them in a mixture of strong acids containing hydrofluoric acid. The as-deposited grain structure of a coating 0.41 mm thick (tube 8) is shown in Fig. 3. It can be seen that the coating is fully dense and has a coarse, columnar grain structure. Mechanical twins, probably introduced during grinding, are visible in some of the large grains near the top surface. The microhardness was 546 DPN, compared with a typical value of 250 DPN for pure rhenium in its most ductile condition. Because vapour deposited materials frequently contain internal stresses and dissolved gases from the deposition process the parts were annealed at a temperature of 1873 K for one hour in a dynamic vacuum of 2 - 4 x 10^{-5} torr, to ensure that they were in the most ductile condition for welding. Thin wall parts were supported on tungsten mandrels to prevent distortion, and no changes in dimensions were detectable after annealing. The resulting microstructure is shown in Fig. 4, and the microhardness was reduced to 487 DPN. Considerable grain growth has occurred, but no porosity is evident.

3.2 Parts made from rolled sheet

The inner and outer pressure case (parts 19 and 13) were too heavy and thick to be made economically by the CVD process and were therefore made by the Thermo Electron Corp., USA from sintered and rolled sheet of 2 mm thickness, supplied by Cleveland Refractory Metals. The sheet was roll-formed to a tube, seam welded by electron beam, and finally ball-drawn to the exact internal diameter to ensure a circular cross section. The parts were finally stress relieved at $1200^{\circ}C$ for 2 hours, and re-checked for circularity. The annular outer case end (part 15) was stamped from rhenium sheet 1.5 mm thick. The three sets of three strut connectors (parts 5, 11 and 20) were made by spark machining from rolled sheet 1 mm thick, followed by diamond lapping to the external radii of the tubes onto which they were welded.

4 JOINING TECHNIQUES

4.1 Electron beam welding of rhenium

Rhenium parts were assembled by electron beam welding at the Welding Institute, Abington, Cambridge, using a Hamilton Standard, 150 kV set with an R40 type electron gun (6 kW) at a working distance of 150 mm. The electron beam process was selected because of the high melting point and chemical reactivity of rhenium, and because of the lower heat input and more accurate control of parameters obtainable on thin sections. Because no results of previous experience of welding rhenium were available, welding trials were carried out on pieces of rolled sheet of representative thicknesses, to establish parameters. In general, it was found that linear welding parameters developed on flat sheet could be applied to circumferential welds, although whenever possible offcuts from the actual parts were used to simulate the geometry. On circumferential butt welds where 100 per cent penetration was required tungsten mandrels were inserted inside the tubes to act as backing bars and prevent drop-through of the weld bead. The microstructure of a butt weld between two offcuts of tube 8 is shown in Fig. 5. There is no evidence of cracking or porosity in the weld zone. To promote degassing from the fusion zone during welding, the beam was spun in a circle of 0.1 mm diameter to give a stirring action. The welding schedules used for the various joints are given in Table 4. To practise assembly and fixture techniques it was found useful to weld up a replica of the resistojet in stainless steel. All welds in the pressure case parts were vacuum leak tested using a mass spectrometer leak detector. The most critical welds as regards degree of mechanical fit and alignment were the stake welds through the thin wall tubes onto the struts. The outer diameters of the three struts were diamond ground to give a tight push fit with the internal diameters of the heater tubes. Since the struts were covered by the tube during welding it was most important to index the angular and axial positions of the struts so that they could be accurately located under the electron beam. In one set of stake welds (tube 17 to struts 11) the tube was severely burned by the electron beam, leading to poor fusion to the struts. This was believed to be due to distortion of the thin wall tubes causing incomplete mechanical contact during welding. At a later stage of assembly these welds sheared apart, but the assembly was completed, relying on the contact resistance of the joint to promote diffusion bonding during testing of the resistojet.

4.2 Brazing

To join rhenium to stainless steel and molybdenum, a gold-18 per cent nickel alloy was used in wire form, and parts were vacuum brazed at 1250 K. To join the stainless steel bellows (24) to the molybdenum stem (25), localized heating had to be used to prevent annealing of the bellows and a resulting change in spring rate. Using the EB welding set, electron beam heating was tried initially to braze the joint. However, the larger thermal mass of the stem prevented the braze alloy from flowing under the bellows, and the end of the bellows distorted under the action of the heating. A large copper heat sink was clamped around the convolutions of the bellows to prevent annealing. The problem was solved by furnace brazing a stainless steel sleeve onto the stem, so that the bellows could be EB welded to the sleeve.

5 CONCLUSIONS

It has been demonstrated that high performance resistojets can be constructed using rhenium for the high temperature heat exchanger parts. Rhenium tubes of high quality, which could not be fabricated in any other way, can be made by the chemical vapour deposition process. Rhenium, unlike tungsten, can be joined easily by electron beam welding.

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APPENDIX

ASSEMBLY PROCEDURE FOR J3 RESISTOJET

All item numbers mentioned in this procedure are according to the PERME Westcott Drawing No. 15189-C. The following procedure need not be considered the only possible sequence of assembly. It is, however, a workable sequence and can save some repetition of steps caused by damage to parts. It is assumed that all parts have been at least roughed out and await finishing to fit other parts as required. Before assembly all parts which require pressure integrity should be leak checked.

STEP 1

EB weld the Nozzle (16) to the Heater Tube (10).

STEP 2

EB weld the Struts 'A' (20) to the Heater Tube (10). After welding, the Struts should be ground to fit the inside diameter of the Heater Tube (9).

STEP 3

EB weld the Struts 'B' (11) to the Heater Tube (9). After welding, the Struts should be ground to fit the inside diameter of the Heater Tube (17).

STEP 4

The Struts 'C' (7) are EB welded to the Heater Tube (17). After welding, the Struts should be ground to fit the inside diameter of the Heater Tube (8).

STEP 4a

This step has been added as the decision has been made to manufacture the Heater Tube (8) in two parts, the Tube and the Flared End. EB weld the Flared End to the Tube. It can be achieved either before or after Step 4.

STEP 4b

Vacuum leak test 4a.

STEP 5

The flared end of the Heater Tube (8) should be ground to fit tightly into the bored end of the Inner Case (19).

STEP 6

The assembly of items 10 and 20 should be inserted into the assembly of items 9 and 11 and EB welded attaching item 9 to item 20.

STEP 7

The assembly in Step 6 should then be inserted into the assembly of items 17 and 7 and EB welded attaching item 17 to item 11.

STEP 8

The assembly in Step 7 should then be inserted into item 8 and EB welded attaching item 8 to item 7.

STEP 9

At this point the assembly should be leak checked on a mass spectrometer leak detector to test leak tightness of welds in item 8.

STEP 10

The whole assembly in Step 8 should then be inserted into and EB welded to the Inner Case (19).

STEP 10a

Vacuum leak test.

STEP 11

The Insulator (18) is now fitted into the Inner Case (19).

STEP 12

The Radiation Shield (21) is trimmed to clear the flared section of the Heater Tube (8) and installed into position.

STEP 13

The Spacer (6) is now installed and the Inner Case assembly gold brazed to the Inner Case Stem (25) attaching the Inner Case to the Inner Case Stem.

STEP 14

At this point the assembly should be leak checked on a mass spectrometer leak detector.

STEP 15

The Bellows (24) is now EB welded to the Adaptor (22).

STEP 15a

Vacuum leak test.

STEP 16

The assembly in Step 15 is now gold brazed to the Inner Case Stem (25) using EB heat or perhaps induction heating.

STEP 17

At this point the assembly should be leak checked on a mass spectrometer lead detector.

STEP 18

The Thermal Dam (3) is now vacuum brazed to the Mount (2) and the joint leak checked on the mass spectrometer leak detector.

STEP 19

The Outer Case (13) is now gold brazed to the Mount (2) and the joint leak checked on the mass spectrometer leak detector.

STEP 20

The Outer Case End (15) should now be finished to fit both the Nozzle (16) and the Outer Case (13).

STEP 21

The assembly as per Step 16 should now be assembled into the assembly as per Step 19 and the length for the Insulator Seal Assembly (23) determined. It should be just long enough to allow a slight clearance for the Bearing (1).

STEP 22

The Insulator Spacer (14) is now installed and the Outer Case End (15) EB welded to the Outer Case (13) and the Nozzle (16).

STEP 23

At this point the assembly should be leak checked on a mass spectrometer leak detector.

STEP 24

The Insulator Bearing (1) and the Insulator Seal Assembly (23) are installed and the Insulator Seal Assembly EB welded to the Adaptor (22) and the Mount (2).

STEP 25

At this point the assembly should be leak checked on a mass spectrometer leak detector.

STEP 26

The Propellant Tube/Power Lead (4) is now silver brazed into the Thermal Dam (3).

STEP 27

At this point a final leak check is made on the whole assembly on the mass spectrometer leak detector.

STEP 28

The Insulation and the Insulation Casing can now be fitted.

TABLE 1

Design parameters for resistojet, J3

	Initial	Revised
Electric power, kW	3.0	3.0
Exhaust velocity, km/sec	8.22	8.09
Inlet temperature, K	300	300
Propellant	H_2	H_2
Mass flow, g/sec	0.0793	0.0806
Thrust, N	0.652	0.652
Propellant supply pressure, MN/m^2 (atm)	0.891 (8.79)	0.345 (3.40)
Terminal voltage, V	15	13.8
Current, A	200	217
Minimum life, hours	2000	2000
Eclipse power interruptions	400	400
Overall mass, g	-	1600
Mass of rhenium parts, g	-	870

TABLE 2

List of resistojet J3 components

Part No.	Material	Mass (g)	Wall thickness (mm)
1	Boron nitride	2.0	-
2	Stainless steel	116.2	-
3	Stainless steel	1.6	-
4	Copper	-	-
5 (3)	Stainless steel	0.3	-
6	Boron nitride	0.7	-
7 (3)	Rhenium (sintered)	0.5	1.0
8	Rhenium (CVD)	30.1	0.41
9	Rhenium (CVD)	5.15	0.165
10	Rhenium (CVD)	9.74	0.70
11 (3)	Rhenium (sintered)	1.0	1.0
12	Stainless steel and insulation	546.5	-
13	Rhenium (sintered)	469.5	2.0
14	Boron nitride	4.0	-
15	Rhenium (sintered)	15.71	1.5
16	Rhenium (CVD)	11.53	0.70
17	Rhenium (CVD)	7.39	0.125
18	Boron nitride	6.0	-
19	Rhenium (sintered)	312.5	2.0
20 (3)	Rhenium (sintered)	0.4	1.0
21	Rhenium (sintered)	12.6	0.025
22	Stainless steel	0.7	-
23	Nilo 36-alumina	8.8	-
24	Stainless steel	1.3	0.127
25	Molybdenum	38.5	-

TABLE 3

Summary of pressure induced stresses in rhenium parts

Part No.	Name	Initial design Pressure 0.891 MN/m^2 Max. Stress, MN/m^2	Revised design 0.345 MN/m^2	Temp K	Allowable stress 2000 hr life MN/m^2
13	Outer case	13.55 to 98.5*	13.30	1000	10.35
19	Inner case	8.49 to 55.1*	5.65	1400	9.18
8	Heater tube	2.14 to 50.2*	6.00	1600	8.69
16	Nozzle (outer edge)	50.0	9.65	1300	9.45
15	Outer case end	64.8	9.60	1150	9.80
10	Inner heater tube	0.048	0.207	2530	5.18

*Depending on calculation treatment at the joint

TABLE 4

Electron beam welding schedules developed for J3 resistojet

Working distance = 150 mm   Beam oscillating frequency = 2 kHz

Joint	Beam voltage kV	Beam current mA	Welding speed m/min	Remarks
Struts (20) to tube (10) Struts (11) to tube (9) Struts (7) to tube (17)	100 140 140	3.0 1.6 1.6	0.5 1.5 1.5	Fillet welds run from both sides of strut, beam tangential to tube, focused on surface with 0.25 mA beam current. To prevent distortion of thin wall tubes a tungsten mandrel was inserted
Circumferential butt weld in tube (8)	100	3.0	0.5	The joint was tack welded at lower power before final run. Slightly defocused beam was used with fade-in and fade-out. Slight sticking to mandrel occurred
Nozzle (16) to tube (10)	100	3.4	0.5	Joint tacked over whole length with 1.5 mA beam. Fade up time 1.5 sec. Weld time 1.3 sec. Beam fade down at 3.0 sec. Penetration 90-95%
Stake weld tube (9) to struts (20)	100	3.0	2.5	Beam run twice at 2.5 mA before final run. On one run, hole appeared at end of run on domed surface
Stake weld tube (17) to struts (11)	100	1.5 2.5	2.5	Very bad burning on all 3 welds. Patching with Re sheet was attempted, but not successful
Stake weld tube (8) to struts (7)	100	3.3	0.5	Two runs at same power in opposite directions
Flared end tube (8) to inner case (19)	100	4.0 to 4.5	0.5	Tube axis rotated at 15° to the electron beam (vertical) to avoid hitting flared end of tube (17). Working distance 75 mm
Outer case (13) to outer case end (15)	100	6.5	0.5	Assembly rotated with axis parallel to electron beam
Nozzle (16) to outer case end (15)	100	2-3	0.5	Assembly rotated with axis at 20° to electron beam (vertical)

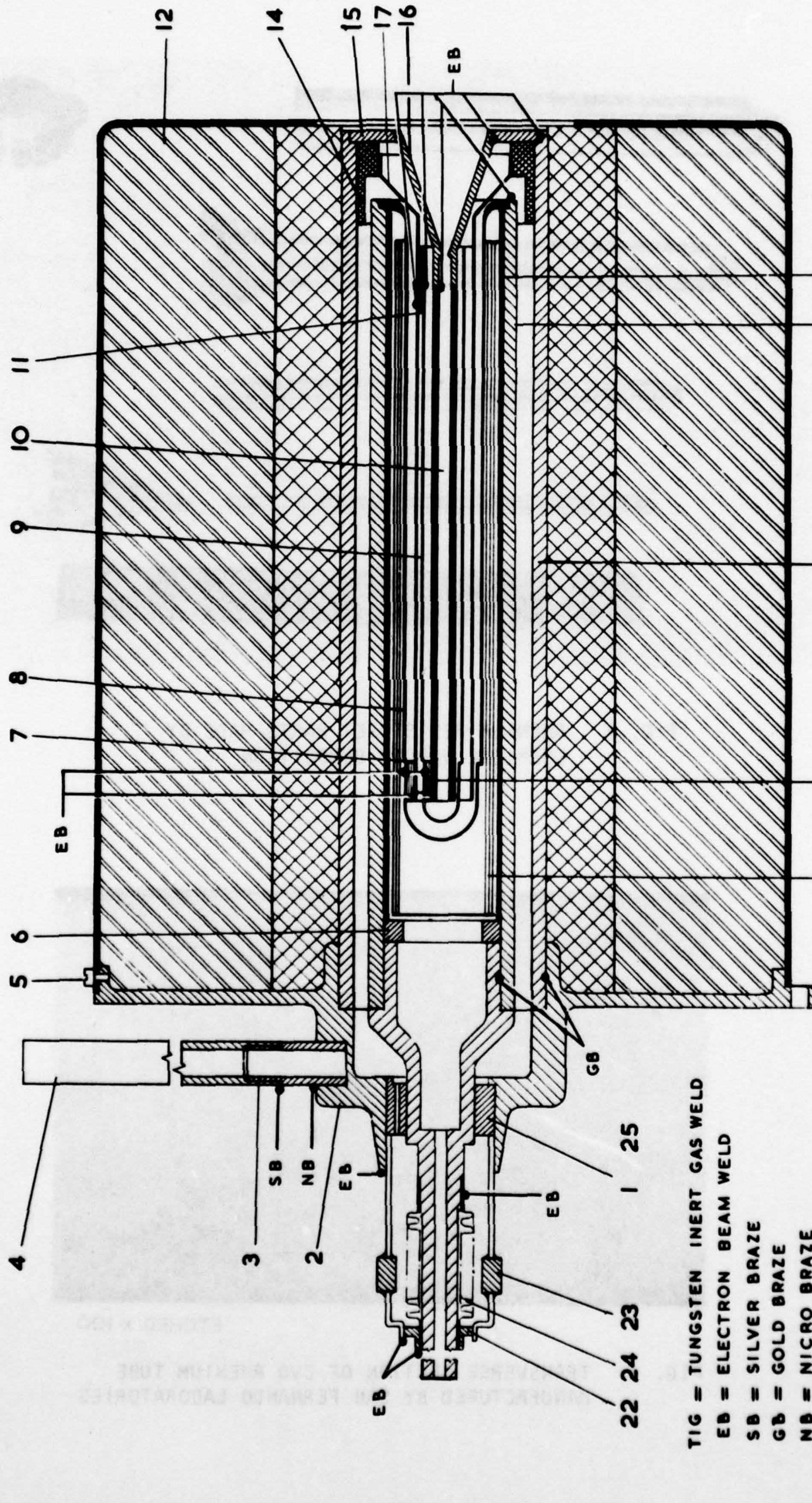

FIG. 1 3 kW RESISTOJET

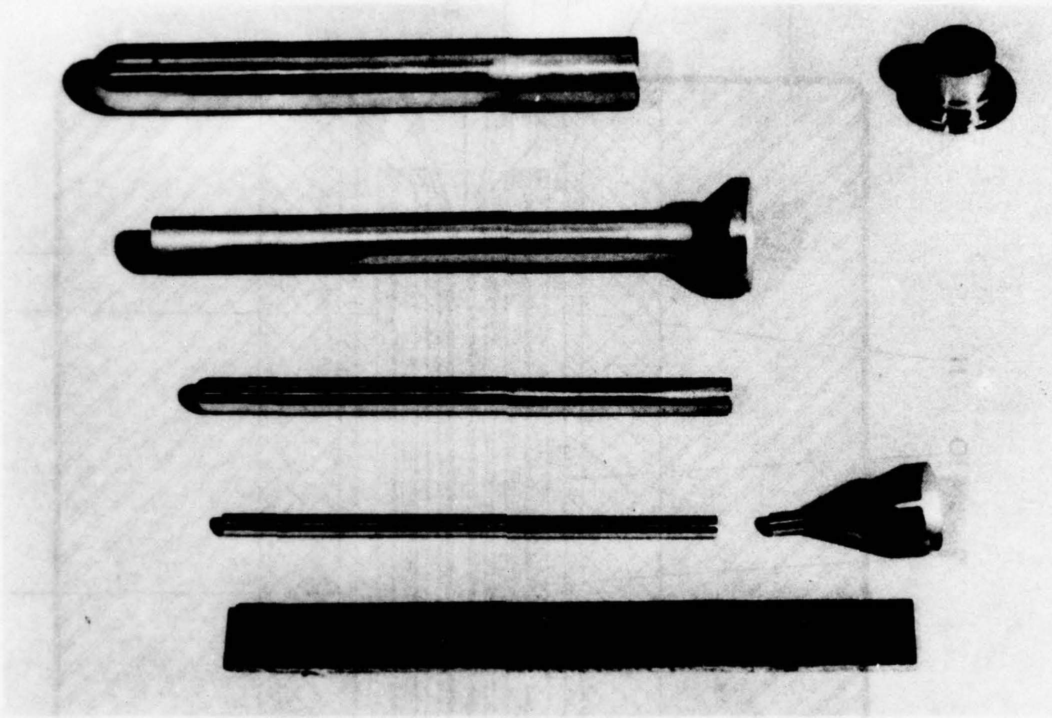

FIG. 2 RHENIUM RESISTOJET PARTS MADE BY CHEMICAL VAPOUR DEPOSITION

ETCHED X 100

FIG. 3 TRANSVERSE SECTION OF CVD RHENIUM TUBE MANUFACTURED BY SAN FERNANDO LABORATORIES

POLARISED LIGHT X 100

FIG. 4 TRANSVERSE SECTION OF CVD RHENIUM TUBE AFTER ANNEALING AT 1873 K

POLARISED LIGHT X 100

FIG. 5 LONGITUDINAL SECTION THROUGH AN ELECTRON BEAM WELD IN A CVD RHENIUM TUBE

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8. Author 1, Surname, initials	9a Author 2	9b Authors 3, 4...	10. Date	pp	ref
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Abstract The fabrication and assembly of a 3 kW resistojet thruster employing hydrogen as a propellant are described with particular reference to the materials problems involved. Rhenium has been selected as the most suitable material for the concentric tubular heat exchanger which must operate at temperatures up to 2500 K in flowing hydrogen for a minimum period of 2000 hours, with temperature cycling.

Because of the complex geometry and close tolerances required, thin walled rhenium tubes were made by a chemical vapour deposition technique. Rhenium parts were joined by electron beam welding.